Automated Multiple Maneuver Optimization (AMMO)

Christopher L. Potts

Introduction

Maneuver optimization was used extensively during tour operations for the Galileo prime mission about Jupiter. A new computer algorithm had been designed to assist in the process of designing orbit trim maneuvers (OTMs) such that the total spacecraft propulsive velocity change (Δv) in the tour would be minimized while satisfying the mission constraints. Mathematical scale factors, or weights, were applied to the Δv components to obtain a nearly direct correlation between minimum Δv and minimum propellant consumption by the spacecraft. It was an exciting time to be involved with the maneuver optimization process and a rare opportunity to immediately apply the results of an optimization analysis to the actual spacecraft trajectory. Unfortunately, the optimization software involved a lot of initial setup, occasionally intense user interaction in the convergence process, cutting and pasting results between different programs, and in general a lot of trial and error.

Two main challenges exist to automate the maneuver optimization process for future missions. The first is to develop an algorithm for specific use in spacecraft operations that reliably converges on an optimal solution in the absence of any external user control. The second challenge is to incorporate the optimization algorithm into a complete automated system designed for robust spacecraft maneuver operations support over the entire mission.

Reliability and speed are critical characteristics of a maneuver and trajectory design system that will be exercised repeatedly during normal operations and with increased frequency as the spacecraft approaches critical mission events such as trajectory correction maneuvers (TCMs), gravity assist flybys, orbit insertion burns, and encounter targeting. The system must also respond to unforeseen events like late orbit determination updates, spacecraft safe mode activities, and mission design changes. An additional bonus would be the ability to analyze case studies such as TCM Go/No-Go decisions or consider the cost to add an optional asteroid encounter to the interplanetary trajectory. Finally, the automated system should work nights, weekends, and holidays so that the analyst doesn't have to.

A prototype system has been developed to accommodate the repetitive nature of maneuver optimization in spacecraft flight operations. The Automated Multiple Maneuver Optimization (AMMO) system has been developed through the InterPlanetary Network and Information Systems Directorate (IPN-ISD) Technology Program in the Navigation and Radio Metrics work area. The prototype system has demonstrated the ability to routinely determine the optimal Δv requirements from updated orbit determination solutions while satisfying the mission specific constraints. The automated nature of the system reduces the design time requirements for commanded Δv by an order of magnitude. The demonstrated turn-around time is 15-30 minutes (depending on the complexity and duration of the trajectory), and subsequently the system is immediately ready to proceed with the next update. User interaction is not required, so the system is operational 24 hours a day/7 days a week for continuous maneuver design support.

Optimization

The structure that defines the optimization problem and the linear optimization algorithm within AMMO were first used in operations during the Galileo mission (References 1-3). Determination of the optimal solution involves breaking the trajectory into discrete segments. A linear model of the segments is passed to the optimization algorithm along with a mathematical definition of the mission imposed trajectory and maneuver constraints. The optimization algorithm performs a sequence of re-weighting iterations to determine the optimal solution to the linear model of the trajectory. The solution is applied to the original trajectory (which can be highly non-linear) and the process repeats until the numerically integrated trajectory segments produce a near continuous trajectory. The trajectory segmenting and loop within a loop iterative approach has proven to be extremely flexible for a wide range of mission applications.

The AMMO algorithm provides the driver and controller of the optimization process to replace the interaction of an experienced user. When the solution to the linear approximation of the trajectory is applied to the original trajectory and numerically integrated, the discontinuities between trajectory segments can increase dramatically rather than decrease, as the linear solution would predict. Unfortunately, this is an all too common occurrence. The AMMO algorithm monitors this behavior and provides appropriate scaling of the linear solution to maintain the iterative path toward trajectory convergence. If necessary, the AMMO algorithm incrementally adjusts the bounds on the linear problem until it determines that the linear solution will improve the discontinuities in the original trajectory. AMMO has the capability to determine final trajectory convergence, and also identifies cases where the discontinuities can be reduced no further due to numerical precision limitations. The AMMO algorithm produces interactive feedback and control of the optimization process in a much more efficient and robust manner than even an experienced analyst can provide.

AMMO System

After developing and improving a robust and automated optimization algorithm for use in spacecraft operations, the next step was to integrate the capability with existing navigation software to demonstrate a prototype system for operations. The integrated system could then be applied and modified to accommodate an actual flight operations environment.

The AMMO system for operations is based upon the ability to start with a very good initial estimate of the optimal solution. Prior to flight operations, the mission design process defines the optimal reference trajectory. This nominal trajectory provides the initial estimates of the key control variables that define the reference mission. The task is to re-optimize the trajectory after incorporating new estimates of the initial spacecraft state and model variations. The spacecraft state and model updates result from the processing of navigation tracking data acquired in flight. With each optimization cycle, a new reference trajectory is created which provides initial control state estimates for use in the subsequent optimization. In this manner a good initial state estimate, which is generally critical for a reliable optimization solution, is routinely available during spacecraft operations.

The focused nature of flight operations combined with a well-defined mission plan provide the framework to apply a software engine that will routinely determine the optimal Δv requirements from updated orbit determination solutions while satisfying the mission specific constraints. The software design accommodates mission inputs as opposed to individual maneuvers, and adjusts the optimization problem definition to fit the epoch of initial conditions as the mission progresses. Most of the model inputs to the software engine occur via standard file inputs. Hence when a maneuver execution date changes, the date is manually changed in an existing maneuver epoch file and all subsequent AMMO solutions will utilize the new date. The AMMO engine constantly checks for notification of a new orbit determination (OD) solution. Currently, a new solution is delivered through a standard electronic form that includes all the navigation files that define the latest estimate of the spacecraft trajectory. The release form is sent by email to the AMMO engine, which identifies the new delivery and immediately begins the re-optimization process.

The prototype AMMO software has been successfully integrated with the navigation software that has been approved for flight missions. While the optimization is occurring within the prototype software, the resulting targets are used as inputs to the navigation legacy software to verify the accuracy of the solution. The re-optimized trajectory results are usually available 15 minutes after the OD file was released. Numerous standard files are produced with each trajectory update. These include the maneuver profile file (commanded Δv for the next maneuver in the mission), a Δv data file of complementary information, and an updated spacecraft ephemeris file spanning the end of the mission. An archive directory is created for each OD solution AMMO receives. If desired, a user can recreate and investigate any optimization result produced by AMMO. The AMMO system also creates status displays of the mission Δv, trajectory control events, a trajectory target plot, and graphical results to quickly observe the efficiency of the optimization process. Since the AMMO system is designed to operate continuously, the engine can send out a short email or alphanumeric page notification of the new Δv solution and the number of iterations required in the optimization process. Figure 1 shows a schematic of the AMMO system.

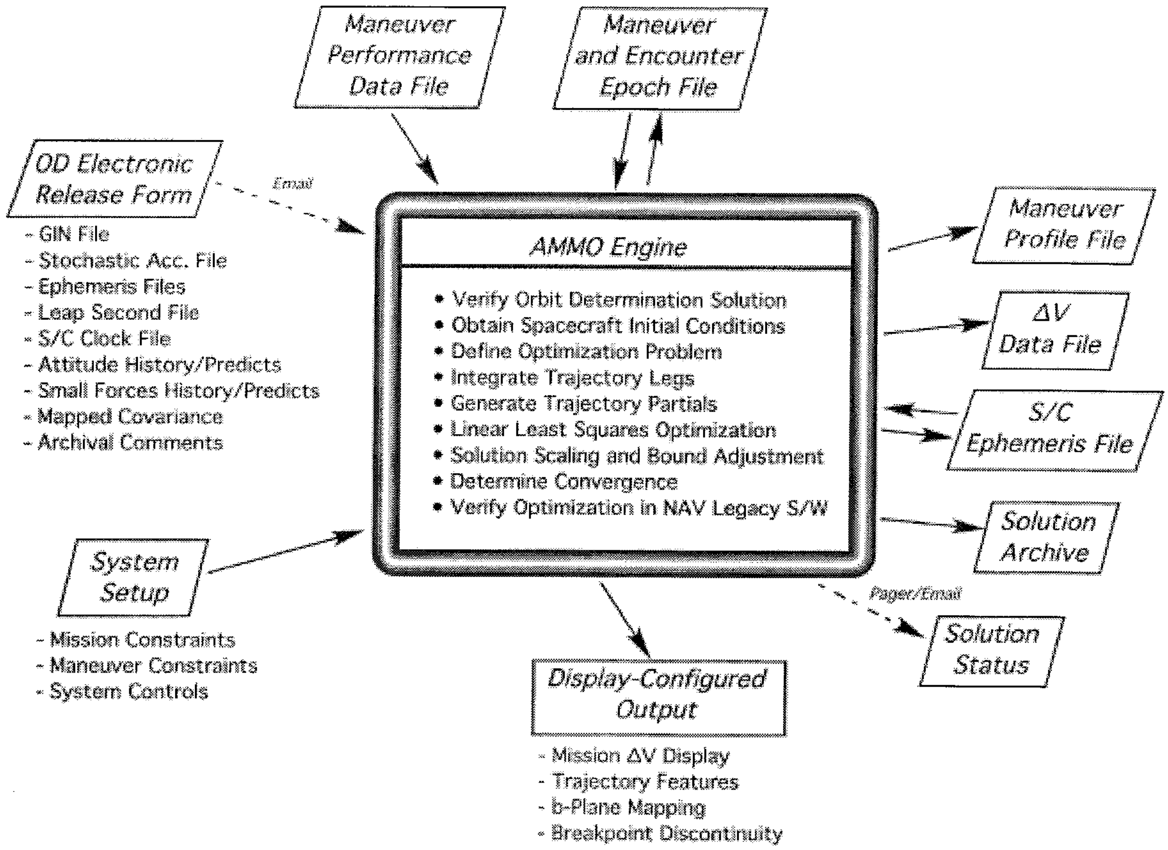

Figure 1: AMMO Schematic

Application

A preliminary Europa Orbiter trajectory provides the ultimate test to date for the AMMO optimization feedback and control algorithm. The highly non-linear trajectory includes approximately 60 trajectory correction maneuvers over a span of 4.5 years from launch to Europa orbit insertion. The dynamic trajectory contains 16 gravity assist flybys with altitudes as low as 100 kilomenters (km), 2 orbit insertion burns (Jupiter and Europa), 2 non-targeted flybys, and a highly sensitive 3rd body capture at Europa. Not surprisingly, applying the linear optimization algorithm to the entire trajectory proved to be numerically unstable. The AMMO algorithm is still able to control convergence in this extreme case. Even with the linear partials continually promoting a divergent solution, the feedback and control algorithm monitors and adjusts the linear bounds to achieve convergence.

From an optimization viewpoint, the Stardust mission trajectory is better behaved and a more stable problem. The AMMO algorithm monitors each iteration, but rarely needs to intervene by applying scale factors or adjusting bounds to the linear solution. The Stardust mission does provide an invaluable opportunity to test the entire AMMO system in a continuous spacecraft operations environment. For over a year now, the AMMO system has been supporting the Stardust mission. During this time, the AMMO system has received approximately 58 orbit determination solutions, and has generated a re-optimized Stardust trajectory usually within 15 minutes of the OD electronic delivery.

The AMMO system has provided maneuver optimization support for the last three trajectory correction maneuvers (TCMs) including a rapid design schedule for the final Earth gravity-assist maneuver. The legacy Navigation software generates the final TCM products based upon the AMMO optimization results. The TCM products receive a complete manual review before delivery, which is currently the most time-consuming aspect of the TCM design procedure. Figure 2 shows the X-terminal located in the Navigation Computing Facility (NCF) devoted to AMMO for Stardust operations. Figure 3 shows the AMMO display results for a preliminary Stardust TCM design.

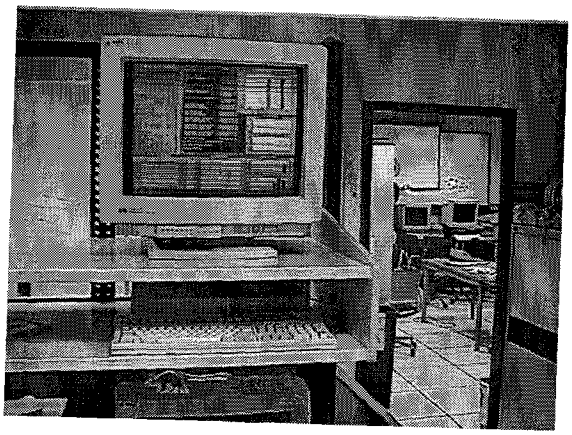

Figure 2: Dedicated AMMO terminal

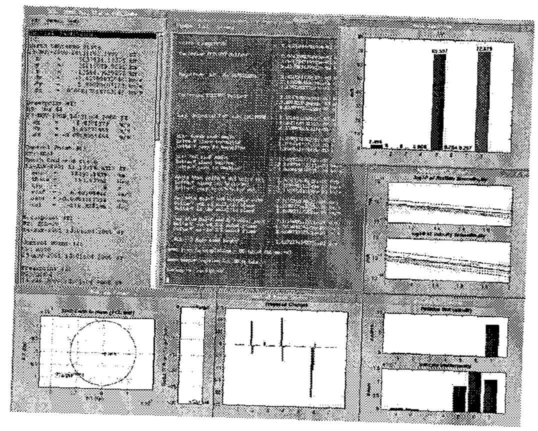

Figure 3: AMMO display

Benefits

An automated ground system for maneuver design significantly reduces workforce requirements, saving time and money. The AMMO system has the potential to ultimately replace a maneuver analyst in the operational determination of trajectory correction maneuvers. The maneuver analyst can place more focus on the critical mission issues and less effort on the repetitive and time-consuming support task of re-optimization. In the current era of multi-mission support, additional efficiencies would result from using the same system for maneuver design across multiple projects. The AMMO capability can also be integrated as part of a complete automated navigation system, with future application toward an autonomous flight system (Reference 4).

The substantial timesaving can also be transferred into mission performance improvements by utilizing shortened TCM design schedules. Later orbit determination tracking data cutoffs can be supported with subsequently improved delivery accuracy for science benefit. For gravity-assist targeting, statistical Δv requirements are reduced as a result of improved delivery accuracy.

An automated system improves maneuver reliability and the efficiency of the design solution. The maneuver support level is elevated to 24 hours a day/7 days a week. Additionally, reference trajectory updates and the subsequent products become routinely available to support Deep Space Network (DSN) predicts and Sequence and Science planning, for example.

Summary / Future Plans

The prototype AMMO system has demonstrated the capability to routinely and automatically re-optimize the spacecraft trajectory in a flight operations environment. This capability has proven to be valuable during time-critical mission events and for extended maneuver analysis support with limited resources. Additionally, the control algorithm provides a systematic and relatively effective approach toward solving complex and numerically unstable trajectory optimization problems.

Future plans include a transition of the AMMO prototype capability into official navigation software and procedures. Currently, there is an ongoing effort to re-implement the legacy navigation software system with a modular design to promote future development efforts. Integration with this task will enable a more efficient AMMO implementation, and eliminate the dual modeling efforts that the prototype system requires to function with the current navigation software. In the meantime, maintenance of the prototype AMMO system improves operational efficiency, and eliminates the need for repetitive manual analysis.

References

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